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Designing public squares with green infrastructure to optimize human thermal comfort

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ABSTRACT

People living in cities are experiencing summerly heat stress situations with severe consequences for their health, especially under climate change. Urban planning needs to address this problem focusing on areas where people are exposed to heat such as in public squares. Typical square designs include green infrastructure which can positively affect outdoor thermal comfort by providing regulating ecosystem services, but knowledge on the effectiveness of different design approaches is still limited. The present study assessed typical greening designs of rectangular public squares and their microclimatic influences during a hot summer day both during day and night-time conditions. By using a validated ENVI-met V4 model, thermal comfort values expressed by the physiologically equivalent temperature (PET) index were compared. Moreover, a novel greening design was developed and tested with the model. The results showed that at 3pm the greening design with most trees and trees placed in the sunlit areas of the square provided 5.2% higher cooling effect compared to the current greening, whereas for 4am the design without trees, but with meadow areas performed best (4.2% heat reduction). This led to the conclusion that for a comfortable thermal situation a climate adapted design has to include trees to maximize the shaded surface areas, while the main wind channel is kept free from trees, but planted with grass to minimize the heat storage. The number of trees and their placement together with the extent and placement of grass areas can thus serve as indicators for designing climate adapted public squares.

1. Introduction

Extreme weather events such as heat waves, i.e. periods of persistent hot weather conditions are among the major natural hazards affecting densely populated cities. Due to climate change their duration, frequency and intensity is expected to rise and already during the last decades an increasing occurrence of heat waves in Europe have been recorded [17,41].

Urban areas with high population and building density are especially vulnerable to summerly heat which can have severe consequences for human health and well-being [18,21,40]. Therefore, adaptation strategies to reduce the negative impacts of heat on the urban population are urgently needed both by adaptation of urban structures and increasing the resilience of its citizens [9].

Various concepts have been suggested to adapt urban structures to extreme heat with measures like modifying the built environment, increasing the share of vegetation or increasing the albedo of surface materials (e.g. Refs. [2,26,33,42,52]. In this context, green and blue spaces have received particular attention as an urban green infrastructure (UGI) due to its potential to regulate the urban climate by shading and evapotranspiration and its multifunctionality in providing different ecosystem services simultaneously (e.g. Refs. [6,15,59].

Within the urban areas public squares should receive special attention when planning adaptation measures to heat waves. Many citizens use these squares regularly to spend leisure time or as a resting place while moving around the city especially during the summer season. Historically, public squares had an important role in cities as focal point for social life. Today, public squares offer space for different uses such as recreation, sport and social activities as well as markets. Depending on the usage and location within the city, the design varies from different geometries to different infrastructures and different planting designs [24].

For all types of public squares it is indispensable to provide comfortable thermal conditions to their users during hot days, under today's and also future climate conditions, when the risk for experiencing heat stress is the highest [19]. So far, several studies have confirmed the cooling effect of UGI while the magnitude of cooling differed depending on the urban form, the type and the extent of vegetation and the time

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period of heat mitigation (e.g. Refs. [27,30,31,36,46,59]. Consequently there has been an increasing attention regarding the microclimatic benefits of UGI in terms of their forms and distribution [49,58]. However, the typical green design of public squares varies widely to accommodate different uses and the design is guided by aesthetic preferences whereas climatic considerations usually have not been a prime concern [8]. Therefore, urban planners need empirical evidence regarding the best UGI design to counteract the climate warming within the public squares that they can readily use in the design process [19].

Against this background, the present study assesses typical greening design options for rectangular public squares as well as an innovative design layout and their microclimatic influences during a hot summer day by applying a validated version of the ENVI-met V4 microclimatic model. Different green designs within the squares differing in their amounts and placements of trees and meadows, were compared. The simulations were evaluated for day and night time conditions to derive holistic recommendations for urban planners regarding comfortable thermal conditions during the whole day on a rectangular square in summer. Finally, it is discussed what type of information on the green design of public squares could serve as indicators for climate adapted squares in future cities.

2. Materials and methods

2.1. Case study area

The study was conducted in Munich (48°8‘N 11°24‘E, 519 m asl), the third largest city of Germany. It is located in the south of the country close to the Alps and densely populated with 1.53 million inhabitants [23]. Its' climate is classified as moderately warm with an average air temperature of 9.1 °C and an annual mean precipitation of 959 mm. During the summer months, the city experiences approx. 8 hot days (with maximum air temperatures above 30 °C) and the urban heat island effect is clearly detectable [1,13].

The city's landscape is characterised by open green spaces, e.g. the Englischer Garten and the riparian zones of river Isar, as well as public squares of different shapes and designs. Due to the large effort and complexity involved in the measurement of climatic variables and microclimatic modelling, the study had to concentrate on one public square. For its selection, we conducted a survey of all public squares (N = 326, [7]; see appendix B and section 2.4). The analysis showed that the majority of public squares in Munich has a rectangular shape (44.5%), whereas 7.4% are of a round shape and 48.1% of varying shapes. Following a discussion with practitioners from the City of Munich, “Bordeauxplatz” was selected as an example for a rectangular shaped square (Fig. 1). It is situated in a densely built district with perimeter blocks towards the eastern part of the city centre and was redesigned in 1998 after historical plans from 1870 (LH [22]. “Bordeaux Platz” has a sky view factor of 0.50 [38]; with matured *Tilia cordata* trees (aged > 40 years) at sufficient numbers and grass lawns as well as frequent public usage.

The buildings in the study area are mainly residential with a height of approx. 18 m (4–5 storey) and some commercial usage in the ground floor. Greenery in the study area is found on the square as well as in the street canyons where single lime trees (*Tilia cordata Mill.*) were planted in the late 1970s along the roads. The streets on both sides of the square run from North to South and from South to North respectively. Bordeauxplatz is planted with a two-rowed lime tree alley at both of the long sides and framed by one-way roads and single streetcar rail tracks at each side. In between the tree alleys there are walking paths with benches, a meadow with flowerbeds and a small water fountain in the centre. The tree covered area reaches 18%, whereas the meadow areas make up for 16% of the area (compare Table 2).

2.2. Urban microclimatic modelling with ENVI-met V4

ENVI-met is a three-dimensional microclimatic model. Among others, i.e. microclimatic effects of urban structures, indoor climate and pollution dispersion, it has been developed to assess outdoor human thermal comfort conditions on certain days and especially, the effects of green elements on different meteorological parameters [3]. Its’ version V4 has been improved especially in representing vegetation processes [27,46] and been evaluated positively for the calculation of bio-meteorological processes when applied in central European cities [12,25]. For the purpose of this study it is hence well suitable.

In the implemented version V4.2.0 the Albero database allows generating sophisticated vegetation profiles; after the simulation process the tool “BioMet” can calculate different thermal comfort indices like UTCI (Universal Thermal Comfort Index) and PET (Physiologically Equivalent Temperature). The use of PET has been recommended by the German guidelines for urban and regional planners for assessing perceived heat sensation of pedestrians [16,28,54] categorised PET index into nine classes of thermal stress - from < 4 °C PET as extreme cold stress to > 41 °C as extreme heat stress with 18–23 °C being the class of comfortable thermal conditions.

2.3. Model configuration and validation

ENVI-met requires meteorological and spatial data for its configuration (Table 1). The meteorological data was extracted from the weather station of the German Weather Service located in the city centre of Munich. To represent a summerly heat stress situation, where people are most at risk of experiencing highest discomfort and which is likely to become more common in the future, a typical hot day with a

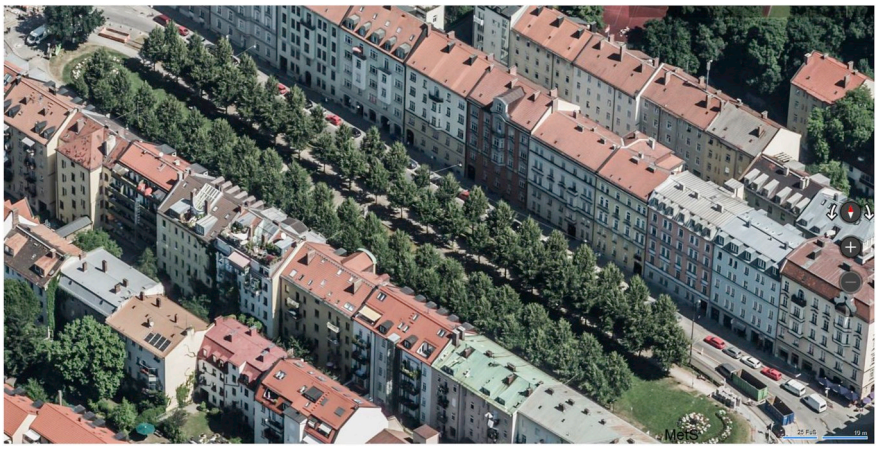


Fig. 1. Aerial photo of Bordeauxplatz, MetS indicates the location of the weather station © 2018 Microsoft Corporation.

Table 1
Model setup and meteorological model input data for ENVI-met V4.

Start of simulation	08/06/2015 at 6 a.m.
Duration of simulations	48 h
Wind speed (10 m above ground)	1.91 m/s
Wind direction	154°
Mean air temperature	26.6 °C
Max. air temperature	35.0 °C
Mean relative humidity	37.7%
Cloud cover	0
Initial soil temperature	Upper layer: 296.5 K; middle layer: 297.3 K; deep layer: 297.0 K
Relative soil humidity	Upper layer: 50%; middle and deep layer: 60%

max. air temperature of 34.8 °C from the summer of 2015 was selected for which simultaneously empirical data from the on-site weather station at Bordeauxplatz was available for model validation [36]. Hot days in Munich mainly take place during stationary temperature inversions with low wind speeds [44].

The weather station at Bordeauxplatz of the type Vaisala Weather Transmitters WXT520 recorded air temperature, air pressure, relative air humidity, precipitation, wind speed and direction during the summer of 2015 in at least 20 m distance to the next tree. Additionally, soil temperature was measured underneath the canopy of selected trees using Tensiomark 1 (4244/1, range pF0-pF7) [36]. To test different settings of the input data after an initial model run, 4 more runs were conducted with adapted settings of either wind direction, soil temperature or combinations of these sensitive parameters. Changes in wind direction can have an influence on the modelling results, as ENVI-met is only able to process a static wind input into the simulation, whereas in reality wind direction changes according to the street canyon settings as well as with the heat loads during heat waves (compare Fig. 2) [12]. The adjustments were as follows: a) initial model run, forced air temperature and relative humidity with 24-h values, average daily wind speed and direction (154°), soil data with default settings; b) same as a) with adjusted soil temperature according to on-site measurements; c) same as a) with adjusted soil temperature and wind direction of 106°; d) same as a) with wind direction of 106° and e) same as a) with adjusted soil temperature and wind direction of 90°. Changes in wind speed were not tested as during hot summer days wind speed is rarely higher than the assumed initial value in this study (compare e.g. Refs. [35,36]. For the selected day the modelled data of a receptor placed directly at the location of the weather station got extracted from all model runs and compared to the recordings of the weather station. Therewith, the model run coming closest to the measured values was identified.

The study area was built into a grid of 225 × 90 x 20 cells and 5 nesting grids to each side with an equidistant horizontal and vertical resolution of 2 m. The lowest vertical grid cell was further divided into five sub-boxes to improve representation of surface processes. To rectify the building structure the grid was rotated 45° from north. Due to the large computational efforts no further simulations with other orientations were conducted. All buildings were set to a height of 18 m made of brick wall with tile roofing. By analysing aerial photos and further confirmed by site visits, 87 lime trees were counted in the case area. In Albero, they were given a height of 20 m with a LAD (Leaf Area Density) of 1.0 m^2/m^3. The crown projection of those trees made up for 18.0% coverage of the case study site, whereas the meadow area greened with grass (LAD of 0.3 m^2/m^3) reached 16.0% coverage.

Simulations were run for 48 h starting at 6 a.m. as recommended by the model developers [3]. For the analysis of the results data of the second day at 4 a.m. (lowest air temperature point of the day), when the model overcame initial transient conditions, and 3 p.m., when highest air temperature point of the day is reached, was selected. PET values were calculated using the BioMet tool for the horizontal layer of 1.4 m height, the centre of the human body [29]. Besides meteorological data, the PET calculation covers the human energy balance, human activities and external factors like clothing [16].

2.4. Green design scenarios

Nine scenarios were defined to test the microclimatic effects of different green designs at public squares. By analysing aerial photographs, all public squares in Munich (n = 326 [7], were classified according to their greening design, i.e. the shape and structure of vegetation on the square. For the most popular square shape – rectangular – the greening design could be further distinguished into 8 varieties, one of them being the current greening situation at rectangular Bordeauxplatz, another one a non-greened version without any vegetation. All 8 varieties represent common green square layouts (see appendix A and B for examples of squares in Munich for each greening design and list of all rectangular squares in Munich with their respective design). The 8 derived greening options were then applied as greening scenarios to the case study (Table 2). As lime tree is a very suitable and common street tree in Munich and its application allows for comparability between the scenarios, all of them use *Tilia cordata* trees as in the current greening scenario. The trees were planted at a distance of min. 8 m to each other and a distance of min. 6.5 m from the next buildings according to German planting guidelines [11]. In the current greening situation the small water fountain in the centre of the square was not included in the model to concentrate on the effects of UGI on the microclimate.

In addition, a new greening design (scenario I in Table 2) as optimised design solution was developed based on the evaluation of the current greening situation (section 3.2). It was assumed to improve the thermal comfort for day and night conditions in the case area and aligned the trees asymmetrically in accordance to the incoming air flow direction. The streets were moved towards the south-western part of the square and separated by a small green stripe. The parking lots were removed and thus the green area of the square was enlarged. The full square was greened with grass and trees were placed in larger distance from each other, which in total reduced the number of trees in the case area. Five scattered single trees were added to the open meadow area of the square.

3. Results

3.1. Model validation

The receptor data was compared to the measured data for the parameters of air temperature (T_a), wind speed (WS), wind direction (WD) and relative humidity (RH) to identify the best model settings. Fig. 2 shows the results for five simulation runs starting on August 6th, 2015. During night hours ENVI-met underestimates T_a by 1.0–1.5 K. This could be due to the limitations of ENVI-met in representing the thermal storage capacity of building surfaces exposed to solar radiation [55]. During daytime ENVI-met first overestimated T_a, then corresponded well until overestimating peak temperatures by 0.1–0.8 K in the afternoon. Comparing the five model runs, run b) with adjusted soil temperature showed the smallest deviations from the measured data. Additionally, the modelled T_a were compared by linear regression to the measured data. Table 3 and Fig. 3 give the coefficient of determination R^2 and the root mean square error RMSE, which are very close for all simulation runs. With a R^2 of 0.94 and RMSE of 1.28 again run b)

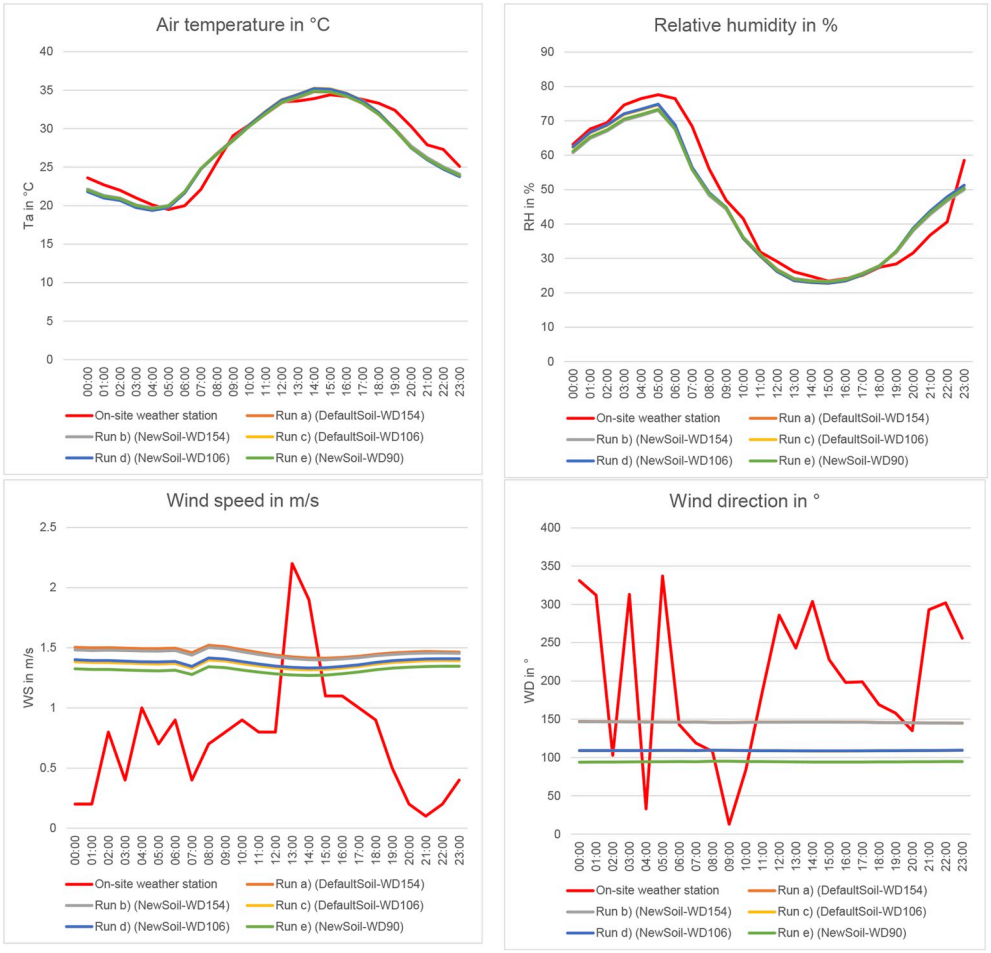


Fig. 2. Comparison of modelled data of five simulation runs with measured data from the on-site weather station.

showed to be the best predictor of the measured T_a in relative and absolute terms (Fig. 3).

As ENVI-met works with a static wind speed and direction input, the results indicated a rather stable development of WS (1.3–1.5 m/s) and WD (100–150°) over the diurnal cycle, which discords widely from the weather station's data that is more variable and reaches values between 0.1 and 2.2 m/s with a clear maximum in the early afternoon hours. For RH, the modelled data corresponded well to the measured data with a slight underestimation before noon and a slight overestimation in the evening.

Generally, this validation study showed good accordance of the modelled data of all five ENVI-met simulation runs with the measured data. As for T_a model run b) showed highest accordance with the measurements, all further simulations in this study were run with adjusted soil temperatures as given in Table 1.

3.2. Thermal comfort at Bordeauxplatz with current greening design

In the following sections the simulation results of PET at 4 a.m. during the night and 3 p.m. in the afternoon are presented as mean, minimum and maximum values for the whole study area. Results are visualised in maps and given as proportionate cover of respective PET classes (Tables 4 and 5 and Figs. 4–6). The cooling potential of the different scenarios is expressed in relation to the results for current greening.

Current greening (scenario A in Table 2) at 3 p.m. leads to an average PET value of 45.2 °C and single values spanning from 37.2 to 62.2 °C. According to Ref. [28] it represents a very hot thermal perception for pedestrians spending time outdoors and even in the coolest areas, PET values did not fall beyond 37 °C consequently indicated strong heat stress. The coolest areas occurred in the shade of trees and buildings, where solar radiation did not reach the ground directly and hence, mean radiant temperature (T_{mrt}) was low. Hot spots of up to 60 °C can be found in areas without trees, of low wind speed and in front of south-western oriented building facades, i.e. in the building corners and narrow street canyons which are exposed to direct solar radiation to heat up the surfaces and re-radiate as long wave radiation. The open spaces in the case area, meadow as well as asphalt area make up for the largest spatial share (almost 50%) with PET values between 47 and 51 °C (see Fig. 5).

At 4 a.m. the situation looked different: the case area has cooled down to 14.4 °C PET on average with 11.6 °C as minimum and 16.7 °C as maximum PET, representing moderate to slight cold stress. During night time the area underneath the tree crowns and around the trees showed to be the warmest as hot air got trapped and hindered from dissipating. Moreover, the areas with poor ventilation in the building corners and narrow street canyons again appeared to be the hot spots. The coolest areas occurred in the well ventilated street canyon, i.e. the broad street canyon oriented in the wind direction. Due to the width of the canyon the street trees planted alongside the buildings only blocked

Table 2
Common designs of rectangular public squares in Munich and application as design scenarios for Bordeauxplatz, including indicators for climate adapted design.

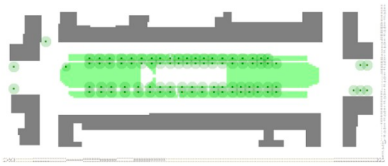
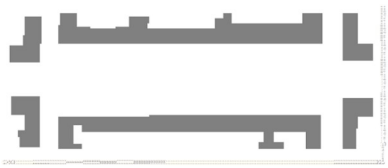
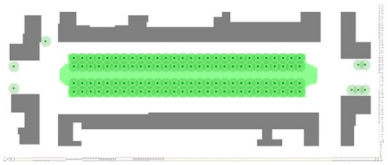
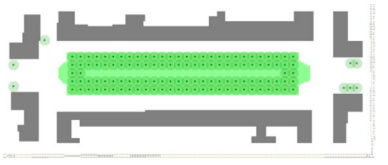
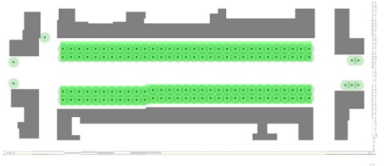
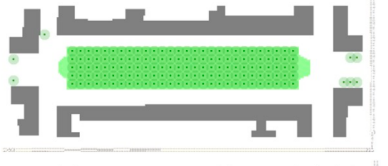
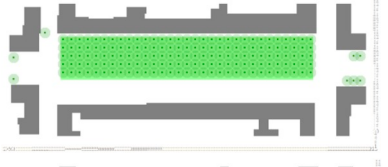
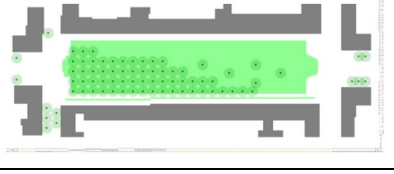
Greening design scenario	Description of typical design	Share of all squares in Munich (n = 326, %)	Green share (%) in spatial design a) Tree crown projected area b) grass area	Number of trees in spatial design	Implementation of spatial design at Bordeauxplatz
A) StatusQuo	Current greening situation at Bordeauxplatz, trees in two short rows along the long sides, in the centre of the square	–	a) 18.0 b) 16.0	87	
B) NoVeg	No vegetation on the square	2.2	a) 0.0 b) 0.0	0	
C) NoTree	No trees on the square, greened with grass	1.2	a) 0.0 b) 22.0	0	
D) TreeRows-open	Trees in two rows along the long sides, in the centre of the square, open edges	4.3	a) 23.0 b) 22.0	112	
E) TreeRows-closed	As D), but rows of trees are at short sides closed to rectangular shape	12.0	a) 24.0 b) 22.0	116	
F) TreeRows-out	Trees in 2 rows on each side of the square, streets in the centre	1.8	a) 25.5 b) 21.0	124	
G) TreesFull	Centre of the square fully planted by trees	5.8	a) 29.0 b) 22.0	140	
H) TreesFull-Side	Trees only on one side of the square, streets on the other side	2.2	a) 32.0 b) 23.0	155	
I) New Design	Trees in asymmetric cluster on western part of the square, eastern part greened with grass and single, scattered trees	–	a) 16.0 b) 27.0	77	

Table 3
Quantitative measures of the performance of the simulations of ENVI-met model based on modelled and measured air temperature for August 6th, 2015 (24 h). R^2 = coefficient of determination and RMSE = root mean square error.

Settings	R^2	RMSE
Run a) (DefaultSoil-WD154)	0.9397	1.2895
Run b) (NewSoil-WD154)	0.9409	1.2770
Run c) (DefaultSoil-WD106)	0.9347	1.3422
Run d) (NewSoil-WD106)	0.9333	1.3569
Run e) (NewSoil-WD90)	0.9357	1.3318

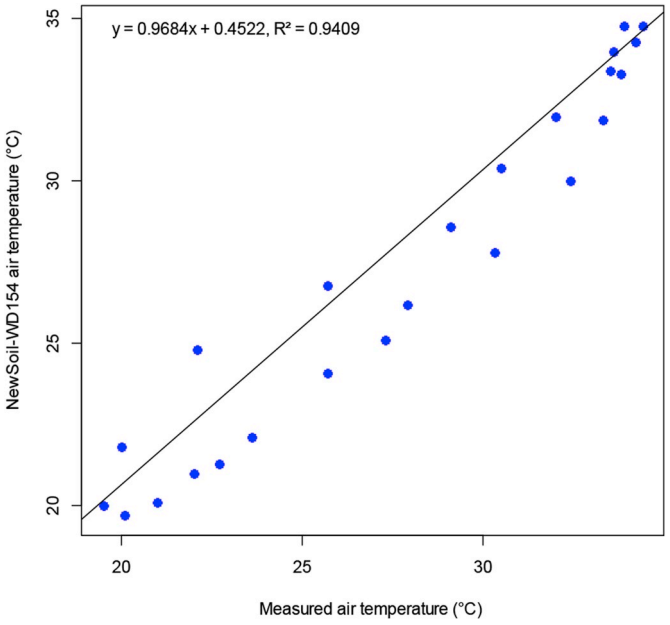


Fig. 3. Linear regression of measured and modelled air temperature for the simulation run b) with adjusted soil temperatures on August 6th, 2015 (24 h). R^2 coefficient of determination.

Table 4
Minimum, maximum and mean PET values at 1.4 m height for the case study area, 3 p.m. of a hot day.

	Min in °C	Max in °C	Mean in °C	Mean relative to Status Quo in %
NoVeg	39.1	63.2	**47.85**	5.89
NoTree	38.59	63.6	**47.67**	5.49
Status Quo	37.22	62.2	**45.19**	0.00
TreeRows-open	36.47	61.4	**43.43**	−3.89
TreeRows-closed	36.49	61.4	**43.34**	−4.09
TreeRows-out	35.74	60.4	**43.18**	−4.45
TreesFull	36.12	61.2	**42.91**	−5.05
TreesFull-Side	35.56	59.8	**42.85**	−5.18
New Design	37.75	62	**45.33**	0.31

the wind slightly from entering the square. Here minimum values of 11.6 °C PET were detected, before it eventually warmed up with the re-radiated heat from the asphalt and dry grass surfaces.

The evaluation of the current greening scenario for both day- and night time showed that different factors are contributing to low PET values and hence more comfortable outdoor conditions: During the day this is mainly shading, during the night an unhindered air flow has the highest impact. Hence, to achieve an optimisation of both situations

Table 5
Minimum, maximum and mean PET values at 1.4 m height for the case study area, 4 a.m. of a hot day.

	Min in °C	Max in °C	Mean in °C	Mean relative to Status Quo in %
NoVeg	11.8	16.87	**14.27**	−0.56
NoTree	11.6	16.48	**13.75**	−4.18
Status Quo	11.6	16.66	**14.35**	0.00
TreeRows-open	11.6	16.59	**14.47**	0.84
TreeRows-closed	11.6	16.59	**14.48**	0.91
TreeRows-out	11.6	16.69	**14.48**	0.91
TreesFull	11.6	16.59	**14.51**	1.11
TreesFull-Side	11.6	16.6	**14.48**	0.91
New Design	11.6	17.19	**14.17**	−1.25

balancing between the different requirements is needed. Based on these findings the 'New Design' scenario as introduced above (see Table 2) was developed, taking up the importance of unhindered air flow in wind direction for night time cooling together with a maximum amount of tree shaded areas for daytime cooling. Further requirements that were fulfilled with 'New Design' are: a) heat trapping underneath the trees should be reduced by planting trees in larger distance from each other; b) the surfaces within the wind channel should re-radiate less heat by planting them with grass; c) a sufficiently wide channel at the north-eastern end of the square should be left open to allow ventilation and d) trees should be placed more strategically to compensate for a lower number of trees in the case area.

3.3. Heat mitigation by alternative green design scenarios

The results of the scenarios showed the potential of different green design options to cool a public square during night- and daytime. They pointed out that differences in amount and location of trees affect the cooling potential.

For the daytime, all scenarios indicated an extreme heat stress situation as all mean values are higher than 41 °C PET with 'NoVeg' reaching a maximum of 47.9 °C PET, which is 5.9% above the value under current greening. In this scenario, the square is fully covered by sealed surfaces. Consequently, cool spots were only found in the shadow of buildings, while the large, sunlit open spaces of the square were strongly heated up. Therefore, with 70% of the surface area this scenario had the largest proportionate cover of PET values between 47 and 51 °C. For the 'NoTree' scenario the mean PET value was only slightly lower than for 'NoVeg' and the spatial analysis showed similar effects of heated open spaces due to a lack of shading, although the open space here is planted with grass. During the hottest hours grass cover did not have any evapotranspirative effect since grass would have hardly any surface soil moisture available. Hence 'NoTree' had no cooling potential, resulting in an increase of PET values by 5.5% compared to the current situation.

All the greened scenarios except the 'New Design' showed improvement in the thermal situation compared to the current one by 3.9–5.2%. The highest cooling potential were showed by the scenarios 'TreesFull' and 'TreesFull-Side', which include the highest number of trees in the case area. In 'TreesFull' the central area of the square is fully planted by trees leading to a closed canopy with a large shading effect. In 'TreesFull-Side' the trees are shifted further to the upper side of the square, moving the shading effect also further up and onto the sunlit building surfaces. This decreased their heat storage and re-radiation potential, resulting in slightly cooler PET values than 'TreesFull'. The scenarios 'TreeRows-open' and 'TreeRows-closed' showed very similar shading and consequently cooling patterns, whereas 'TreeRows-out'

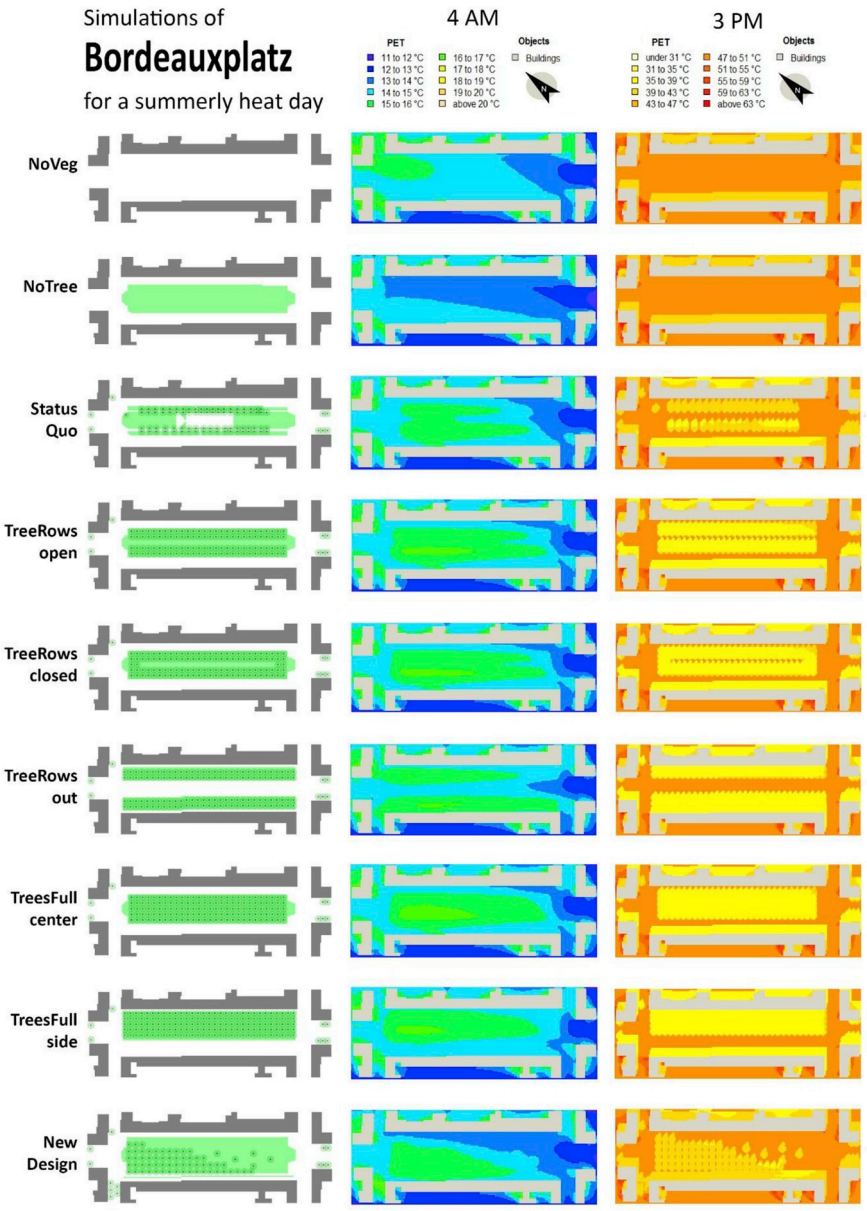


Fig. 4. Spatial maps of PET distribution (at 1.4 m height) in the case area for 3 p.m. and 4 a.m. of a hot day.

performed slightly better. The tree rows in the upper part of the square again shade the building surfaces there, subsequently reducing short-wave input as well as re-radiation of long wave heat towards the square. Moreover, in all greened scenarios higher RH values due to the transpiration of the trees were detected. The cooling potential of the trees caused an increase in the proportionate cover of PET values between 35 and 39 °C, therewith providing more open space with only strong heat stress but not extreme heat stress.

The 'New Design' had with an average PET of 45.3 °C, a slightly reduced cooling potential compared to the current greening situation. Due to the asymmetric design of the trees on the square the other half of the square remains open and is heated by incoming solar radiation except of the shadow area of the single trees. This led to a reduction of the area with PET values lower than 39 °C, while the area with extreme PET values above 43 °C was not increased. Compared to the current greening, the area with PET values between 39 and 43 °C was enlarged.

For the night time, all scenarios resulted in a slight cold stress with average PET values between 13.8 and 14.5 °C at 4 a.m. The cooling potential at this time of the day is strongly related to the presence of trees and grass. As trees trap hot air underneath their crowns, their presence has a negative effect on cooling the square. On the other hand, grassed areas store less heat than sealed surfaces during the day and thus, emit less heat during the night. The highest cooling potential is hence provided by 'NoTree', which is only planted by grass. Here the average PET is 4.2% lower than in the current greening scenario. The air flow moving in wind direction heats up only marginally over the meadow area and reaches the northern part of the square with PET values of 13–14 °C. The warmest spots in this scenario occurred in building corners and narrow street canyons like in the current greening scenario. All scenarios with more trees than the current greening resulted in warmer thermal conditions. Depending on the location of the trees in the scenarios the ventilation of the square is blocked and the

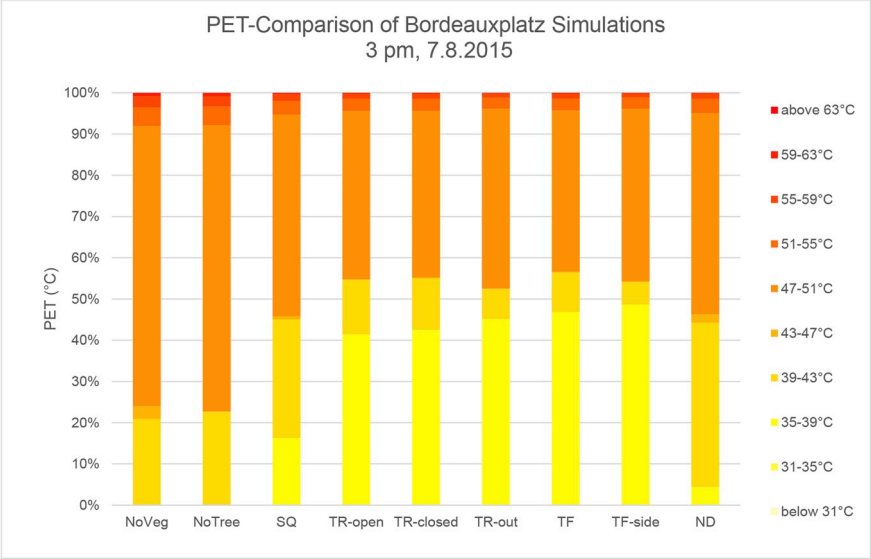


Fig. 5. Distribution of different thermal comfort situations (PET at 1.4 m height) within the case area's open spaces for 3 p.m. of a summerly hot day.

cool air flow cannot cross the whole square as the wind speed on the investigated hot day was too weak to transport cool air further and to replace warm air trapped underneath the trees. When trees are planted in rows as in 'TreeRows-open', 'TreeRows-closed' and 'TreeRows-out' and canyons without trees are left open the cooling performance was better than if the trees are planted in clusters ('TreesFull'). For all treed scenarios the area with PET values of 14–15 °C had the largest share.

As 'New Design' contains fewer trees than the current greening it can reduce PET values by 1.3% less. Due to the open meadow area in the wind direction the cool air can flow through the whole square, even reducing heat in the small street canyon at the northern end of the square. Nevertheless, the warmest areas still occur in the area of the tree cluster, but due to the larger distance of the trees to each other hot spots inside the tree cluster are prevented.

4. Discussion

4.1. Effects of different greening designs within a square on human thermal comfort

This study showed that the outdoor thermal comfort situation of a rectangular square is dependent on the arrangement of its UGI. Variations in the amount and placement of vegetation, i.e. urban trees and lawn areas lead to differences in PET values during day and also at night time. Importance of vegetation as the most prominent elements for heat mitigation especially during the day time has already been reported for street canyons and courtyards (e.g. Refs. [27,53]; however, quantity and quality of greenspace and their arrangement both spatially and temporally as a holistic element are proposed in the current study.

For heat mitigation in the afternoon hours of a hot day, the results of this study indicated that it is most effective to have a high number of

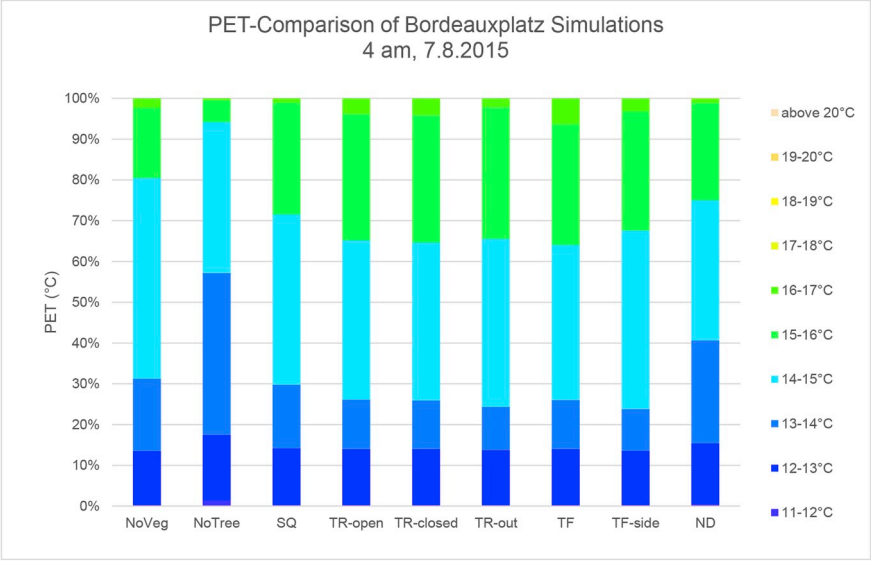


Fig. 6. Distribution of different thermal comfort situations (PET at 1.4 m height) within the case area's open spaces for 4 a.m. of a summerly hot day.

trees and therewith increase the crown-shaded area, as the 'TreesFull-side' scenario with most trees of all scenarios had the lowest PET value. This is in line with several other studies such as [30,37] or [2] reporting that an increase in tree coverage increases the boundary layer cooling during the day. The trees' shading effect is the most prominent form of cooling during day time as in the shadow T_{mrt} values decreased significantly (e.g. Refs. [25,33,35]. This becomes evident, when looking at 'New Design' compared to the other greening scenarios. 'New Design' is the only scenario, which concentrates trees only in one part of the square, leading to a lower tree crown projected area and higher T_{mrt} values in the part without trees. Hence, the average cooling potential remained lower than for scenarios with trees distributed over the square.

However, comparing the results of scenarios 'TreesFull' and 'TreeRows-out' showed that not only the number of trees but also the location of the trees has an influence on heat mitigation [5,19]. 'TreeRows-out' places the trees in the north-eastern part of the square, where T_{mrt} values were very high due to sun exposure in the afternoon and therefore PET reduction was almost the same as for 'TreesFull' with 16 more trees. Moreover, the maximum cooling effect can be achieved with trees planted in clusters, but in sufficient distance from each other. Even though 'TreesFull-side' has 15 trees more than 'TreesFull' placed in the north-eastern part of the square, the difference in heat reduction remained marginal with 0.06 K PET. This leads to the conclusion that the number of trees is not in a linear relation to heat mitigation in the afternoon as already suggested by Ref. [59]. Moreover, the results are in line with other studies, e.g. Refs. [49,58]. They showed that trees planted with sufficient distance to each other and not overlapping crowns have larger cooling effects as the area shaded by the trees is maximised. Additionally, this result confirms the higher transpirational cooling effect from individual trees due to oasis effect [39].

Cooling a square at night effectively requires measures which are in conflict with measures for day time cooling. The higher the number of trees in the scenarios the lower is the heat reduction at 4 a.m. Warm air gets trapped underneath the tree crowns, especially when planted in clusters, and cannot be removed on hot days with low wind speeds. This effect is particularly pronounced at night time since the air is more stable and the depth of cooled air is shallower. Moreover, reduced convection also lowers the wind speed [34]. Even though the street canyons show wind tunnelling effects particularly during the day time, along with the stability of the lower atmosphere these effects are weakened at night. This situation becomes more severe, when trees are planted into the wind channel of the square, e.g. in scenarios 'TreesFull' and 'TreeRows-out'. Thus, for night time cooling it is important to ensure sufficient ventilation as also suggested by Refs. [5,49].

Another interesting result for night time cooling was that grass planted as meadow area on the square improves the heat mitigation. When 'NoTree' is compared to 'NoVeg' it can be seen that the air flow heated up less over the meadow areas in 'NoTree' than over sealed surfaces due to lower heat emissions from the natural surface [14]. Therefore cooling effects can be increased with planting grass, which was also found by e.g. Ref. [27].

Generally, the cooling effect can be further increased by planting trees over grass surfaces. Firstly, grass surfaces are not regarded as heat sources compared to paved surfaces [14]. Secondly, without water stress, grass evapotranspiration can have even higher influence than the tree transpirational cooling in terms of human thermal comfort especially at 1.5 m height as found by Ref. [35]. Thus, by planting the tree pits with grass or into a meadow area, additional heat reduction can be achieved.

This study is novel since it not only assessed typical greening designs found for rectangular public squares but also proposes an innovative approach for designing climate adapted public squares for both day and night time thermal comfort. To achieve thermal comfort of a public square at day and night-time none of the typical greening design investigated in the present study delivers an optimal cooling potential. With 'TreesFull-side' the best day-time cooling can be provided, whereas with 'NoTree' the reduction of PET during night-time is the highest. The innovative 'New Design' is a first attempt to counterbalance the requirements of day and night-time cooling of a public square and detaches itself from the typical greening designs identified for rectangular squares at least in Munich. Additionally, 'New Design' takes up the currently prevailing design modules of the square (sunny meadow areas, shaded areas underneath the trees) and optimises them to provide comfortable conditions at every time of the day. These results indicated that in future climate adapted cities public squares will have to be designed differently than today and that decision-makers will need to think outside the box to achieve optimal thermal conditions.

4.2. Limitations of the methodological approach

The present study has applied the ENVI-met V4 model, validated for T_a and RH, for a rectangular square in a central European city. For T_a, the validation results are similar to the results presented by Refs. [25,47]. This compensated partly for the missing validation of T_{mrt} values, an important parameter for the calculation of outdoor thermal comfort [25], due to limited empirical data. As the model uses a static input for wind speed and direction the validation study showed the difficulties of the model in projecting the dynamic behavior of wind in street canyons over the day. This was also reported by other studies such as [12]. Due to this limitation it was important to test varying input data beforehand and identify the dominant wind direction for the investigated square, as this is a decisive factor for the placement of trees in a climate adapted design.

Moreover, this study focused on the impact of differing green designs on the microclimate of public squares and thus, impacts like square orientation or canyon ratio, investigated e.g. by the studies of [4,27,45] or [10] were not yet taken into consideration; however, could be analysed in further simulations. Additionally, further simulations could be conducted to test the effects of different species of vegetation with i.e. varying crown geometry and LAD values resulting in different cooling potentials as e.g. studied by Refs. [5,31,43] and [58]. In these studies lower LAD values could for example influence the shading intensity during the day, but also the heat trapping during night. Often a mix of different tree species is found in public squares, hence testing scenarios with a more heterogeneous UGI could be another objective for future research (compare to e.g. Refs. [32,48,51].

4.3. Planning recommendations for designing climate-adapted (rectangular) public squares

This study focused on the microclimatic effects of different greening designs for a rectangular public square on a hot summer day and therewith identified general principles of climate adapted design that can be transferred to similar squares elsewhere. The results indicate that some important considerations should be taken into account before planning a climate adapted and thermally comfortable public square by implementing UGI measures and adds to the guidelines presented by Ref. [19] for city, park and street scale. First, the question, whether heat mitigation during the day, at night or for both situations should be prioritized as effective measures differ from each other and might even be contradictory, needs to be addressed. During the day, the most important factor is shading which can be improved by additional trees

placed into the sunlit areas of the square. Moreover, poorly ventilated, but sunlit areas such as building corners should receive special attention to prevent overheating. During the night, the most important factor is ventilation to allow air to flow through the square and distribute hot air from underneath the tree crowns. Therefore, decision-makers need to identify the main wind channel and main wind direction at the specific square and leave this area open from trees. Additional cooling can be achieved by planting meadow areas of grass into the wind channel. In an optimal green design for climate adapted public squares shading and ventilation are ensured at the same time resulting in heat mitigation during the day as well as during the night. This may lead to green designs that differ from typical designs (e.g. scenarios presented in Table 2) resulting in new designs (e.g. as developed for the scenario 'New Design') to integrate the perspective of climate adaptation. Recognition of the importance of landscape design has already put strategic planning at the very core of landscape management practices. However, this needs to be adapted to the local context [56]. With the advent of vertical urban densification, increasing the green share and air flow within the street canyons will be equally important in future cities at least for human thermal comfort. Therefore, spatial distribution of trees and urban lawns to optimize the benefits are of utmost importance as shown in the present study.

As with climate change also the probability of dry summers rises in central Europe, every decision for preserving existing and implementing additional UGI in cities needs to go along with considerations of water supply for the vegetation and occasionally the installation of irrigation techniques as UGI is only able to deliver its services when it stays vital during dry seasons [14,20].

Besides taking design decisions from a thermal comfort point of view as focused in this study, urban planners need to consider other aspects that play an important role for developing well usable public squares and balance them with each other in their design. As public squares are used for diverse activities and during all seasons of the year, the optimal design to mitigate summer heat should also provide sufficient open space for diverse user preferences, e.g. open spaces for sport activities or recreation in sunlit areas during spring and autumn season, as suggested with 'New Design' [57]. for example provided information on the effects of vegetation on thermal comfort in summer as well as the winter season. Further research on the requirements of green public squares needs to be undertaken. If decisions are taken to increase the amount of vegetation, and especially trees, on a square potential disservices of the vegetation such as increase of pollen or higher maintenance costs need to be considered as well [50].

5. Conclusion

This study investigated typical greening designs of a representative rectangular public square and their microclimatic influences during a hot summer day both during day and night-time conditions. A novel greening design was developed and tested with the aim of optimising the thermal conditions at both time steps. It shows that number and placement of trees as well as share and placement of meadow area are important indicators to characterise the thermal comfort conditions at a public square. Considering several other studies this leads to think that increasing the number of trees can be considered as a single most important indicator for thermal comfort of the inhabitants. However, the present study added on that by showing the importance of open grass meadows for better wind flow and less heat storage at least for night time cooling. It further added a more in-depth understanding on the spatial configuration of these elements (depending on wind direction and shading, in particular) and a quantification of the differences between the various scenario designs.

The trade-offs between the two indicators of number of trees and meadow areas need to be considered for optimising the public square design especially at the advent of densification of urban areas and climate change. Taking these concerns seriously in public square design will change the greening design from traditional models to innovative layouts as suggested in this study. Future public square design should aim to reach an optimum of thermal comfort at day and night by strategic placements of trees to cover maximum shaded coverage with minimum hindrance to air flow as well as incorporating grass meadows.

Research should further investigate the optimal public square design depending on orientation and main wind direction as well as choice of tree species.

Declarations of interest

None.

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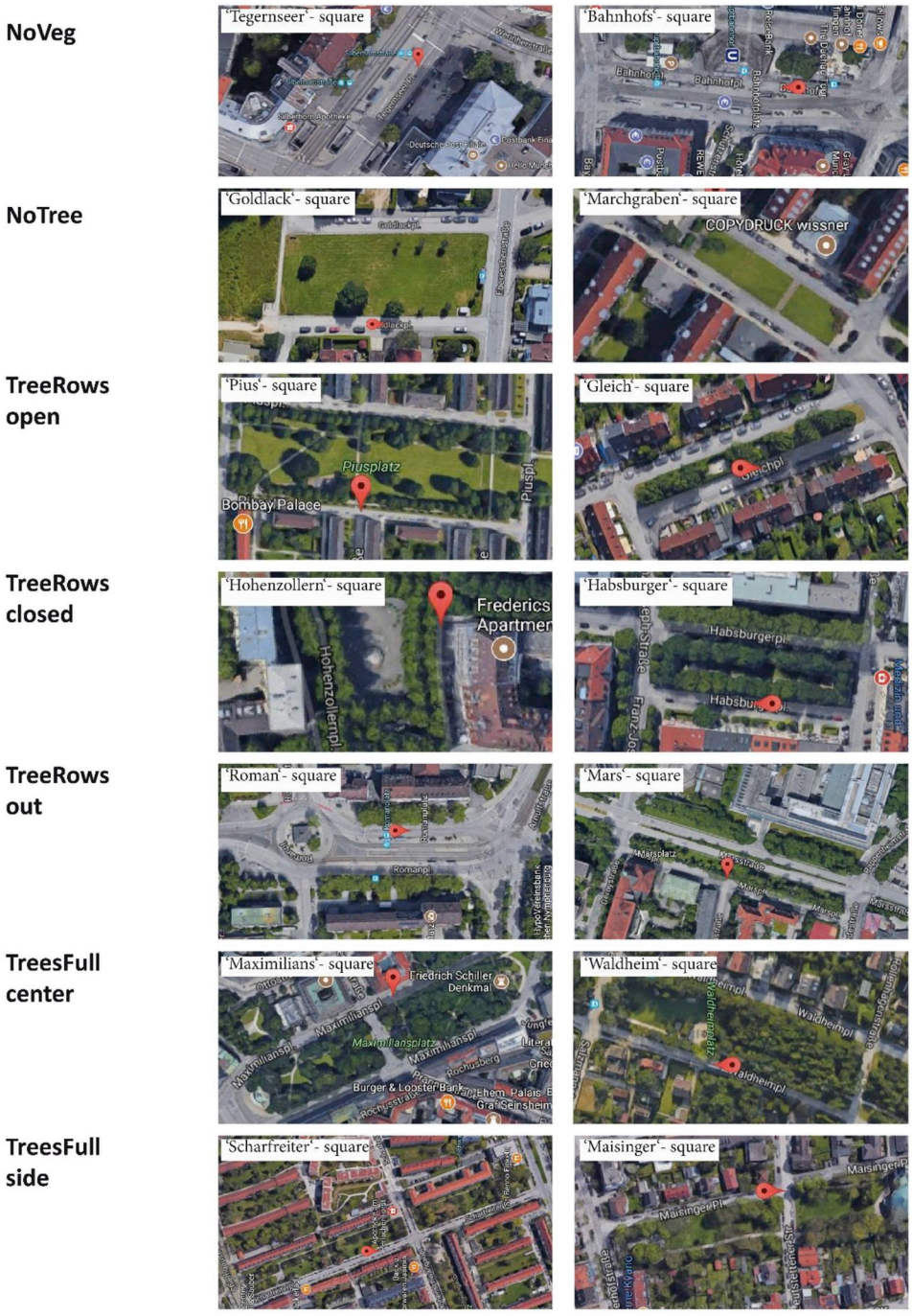
Appendix



Appendix A. Examples of green designs at public squares in Munich, Germany, © 2018 Google Maps, map data: 2018 COWI, GeoBasis-DE/BKG (©2009), Google

Appendix B. Classification of all rectangle public squares in Munich according to their green design

Rectangle squares in Munich	NoVeg	NoTree	TreeRows-open	TreeRows-closed	TreeRows-out	TreesFull	TreesFull-side	Others
(Percentage of rectangle squares)	(4.8%)	(2.8%)	(9.7%)	(27.0%)	(4.1%)	(13.1%)	(4.8%)	(33.8%)
Agnes-Bernauer-Platz 80687								x
Agricolaplatz 80687								x
Alpenplatz 81541								x

Amiraplatz 80333								X				
Artur-Kutscher-Platz 80802												x
Athener Platz 81545												x
Aussiger Platz 80937			x									
Bahnhofplatz 80335	x											
Bastian-Schmid-Platz 81477								x				
Bleibtreuplatz 81479			x									
Böhmerwaldplatz 81679					X							
Bordeauxplatz 81667												x
Brachvogelplatz 81243								x				
Bruno-Hofer-Platz 80937			x									
Burgerplatz 80687					X							
Chemnitzer Platz 80992			x									
Christoph-von-Gluck-Platz 80807												x
Claudiusplatz 80992												x
Edinburghplatz												x
Eichendorffplatz 81369			x									
Elisabethplatz 80796								x				
Esplanade an der Ganghoferstraβe							x					
Feilitzstraβe										x		
Frankplatz 80939			x					x				
Friesplatz 81827												x
Fröbelplatz 80686												x
Genfer Platz 81476												x
Georg-Deschler-Platz 81245					X							
Georg-Freundorfer-Platz 80339					x							
Gleichplatz 80999			x									
Glogauer Platz 80997					x							
Goldlackplatz 80935		X										
Gollierplatz 80339								X				
Gotzinger Platz 81371												x
Graf-Spee-Platz 81827					x							
Griechenplatz 81545												x
Grohplatz 80939					X							
Grünstadter Platz 81539					X							
Habsburgerplatz 80801					x							
Halligenplatz 81825												x
Harnierplatz 80939												x
Hermann-Hahn-Platz 81477												x
Hertwigplatz 80997								x				
Hieberplatz 81247										x		
Hochvogelplatz 81547								x				
Hohenschwangauplatz 81549												x
Hohenzollernplatz 80796					X							
Hönigschmidplatz 80689							x					
Immermannplatz 81247					x							
Implerplatz 81371					x							
Jakob-Gelb-Platz 81543												x
Joergplatz 80689										x		
Kaiser-Ludwig-Platz 80336			x									
Kaiserslauterner Platz 81541					X							
Karneidplatz 81547												x
Kidlerplatz 81371								x				
Klausener Platz 81547		X										
Kölner Platz 80804			x									
Korbinianplatz 80807					x							
Kosegartenplatz 81739					x							
Krempelhuberplatz 80935												x
Kulmbacher Platz 81549												x
Laurinplatz 81545												x
Leonrodplatz 80636												x
Levkojenplatz 80689										x		
Loehleplatz 81671								x				
Ludwig-Ferdinand-Platz 80638					x							
Luise-Kiesselbach-Platz 81377	x											
Maisinger Platz 81477										x		
Mangfallplatz 81547												x
Marchgrabenplatz 80805		x										
Maria-Eck-Platz 81825					x							
Marienplatz 80331	x											
Marsplatz 80335							x					
Maximiliansplatz 80333								x				
Mettenleiterplatz 80939												x
Miesbacher Platz 81547												x
Nederlinger Platz 80638								x				
Neufriedenheimer Platz 81375					X							
Nikolaiplatz 80802					x							
Normannenplatz 81925												x
Nothkaufplatz 81375												x
Oberhofer Platz 80807												x

Odeonsplatz 80539	x															
Oertelplatz 80999		x														
Onyxplatz 80995													x			
Otto-Engl-Platz 81241					x											
Pachmayrplatz 81927					X											
Pfaffenhofener Platz 80686															x	
Pfarrer-Steiner-Platz 80933	x															
Pfrontener Platz 80686															x	
Pippinplatz 81475															x	
Piusplatz 81671				x												
Posener Platz 81929				x												
Posseltplatz 80634															x	
Promenadeplatz 80333											x					
Pronnerplatz 80687															x	
Pündterplatz 80803					x											
Redlingerplatz 81735					x											
Regensburger Platz 81679					x											
Romanplatz 80639							x									
Sanderplatz 81247															x	
Scharfreiterplatz 81549													x			
Schmorellplatz 81545															x	
Schöpferplatz 80992															x	
Schüleinplatz 81673					X											
Sebastiansplatz 80331	x															
Seydlitzplatz 80992					x											
Shakespeareplatz 81679					x											
Simmerleinplatz 80992											x					
Simon-Knoll-Platz 81669							x									
Skabiosenplatz 80995											x					
Specklinplatz 81377															x	
Spengelplatz 80937					X											
Spindlerplatz 81477															x	
Sponeckplatz 81245															x	
St.-Martins-Platz 81541							x									
Stahleckplatz 81375					x											
Steinbeisplatz 80686															x	
Tannhäuserplatz 81927															x	
Tassiloplatz 81541					X											
Tegernseer Platz 81541	x															
Tizianplatz 80638					x											
Trakehner Platz 81929					x											
Überseeplatz 81825					x											
Viebigplatz 80686															x	
Viktoriaplatz 80803															x	
Von-Goebel-Platz 80638					X											
Walchenseeplatz 81539															x	
Waldheimplatz 81739											x					
Wallensteinplatz 80807				x												
Wartburgplatz 80804											x					
Weißenfelderplatz 80686					x											
Wensauerplatz 81245											x					
Wessobrunner Platz 81377					x											
Wettersteinplatz 81547															x	
Winthirplatz 80639					X											
Wittelsbacherplatz 80333				x												
Würmseeplatz 81476															x	
Zita-Zehner-Platz 81541											x					

Appendix C. Mean values of T_a, T_{mrt}, RH and WS for all simulated scenarios

Szenario	Bordeauxplatz: mean values at 3 p.m. in 1.4 m height				Bordeauxplatz: mean values at 4 a.m. in 1.4 m height			
	T_a (°C)	T_{mrt} (°C)	RH (%)	Wind speed (m/s)	T_a (°C)	T_{mrt} (°C)	RH (%)	Wind speed (m/s)
NoVeg	33.46	70.7	22.64	1.19	19.58	10.64	69.16	1.21
NoTree	34.39	69.99	22.59	1.12	19.61	10.02	71.61	1.14
Status Quo	34.17	63.2	23.17	1.15	19.72	11.82	70.74	1.18
TreeRows-open	34.93	59.47	23.76	1.14	19.69	12.34	71	1.17
TreeRows-closed	34.91	59.3	23.81	1.14	19.69	12.38	70.99	1.17
TreeRows-out	34.89	58.83	24.12	1.13	19.72	12.42	71.19	1.16
TreesFull	34.78	58.44	24.22	1.14	19.69	12.5	71.09	1.17
TreesFull-Side	34.83	58.1	24.08	1.17	19.59	12.49	71.35	1.19
New Design	35.03	62.58	23.49	1.09	19.62	11.6	71.88	1.12

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